Project number DE-FE0009738

Area 4 — Enhanced Simulation Tools to Improve Predictions and Performance of Geologic Storage: Coupled Modeling of Fault Poromechanics, and High-Resolution Simulation of CO_2 Migration and Trapping

Ruben Juanes
Bradford H. Hager
Massachusetts Institute of Technology

DOE/NETL Carbon Storage R&D Project Review Meeting
Pittsburgh, August 19, 2015

Benefit to the Program

- **Area of Interest 4:** Enhanced simulation tools to improve predictions and enhance performance of geologic storage

- Support the Goal of development of Best Practices Manuals, and contribute to the Goal of demonstrating 99% storage permanence, by providing advanced simulation tools to <u>understand and predict fault motion, fault transmissivity, and induced seismicity</u>.

- Develop technologies to estimate storage capacity and to improve storage efficiency making substantial advances in <u>understanding capillary and solubility trapping during the post-injection period</u>, and the impacts of aquifer heterogeneity and hydrodynamic instabilities on migration distance.

Project objectives

- **Overall objective:** develop tools for better understanding, modeling and risk assessment of CO_2 permanence in geologic formations

- Specific technical objectives:
  1. Develop efficient mathematical and computational models of the <u>coupling between CO_2 injection and fault mechanics</u>, which will enable assessing the potential for fault slip, leakage, and induced seismicity
  2. Develop <u>high-resolution computational methods of CO_2 migration</u> during injection and post-injection, for better predictions of capillary and solubility trapping at large scales and in the presence of aquifer heterogeneity
  3. <u>Apply the models</u> of fault poromechanics and CO_2 migration and trapping to synthetic reservoirs as well as actual deep saline aquifers in the continental United States

An important scientific question

- Can CCS be a bridge solution to a yet-to-be-determined low-carbon energy future?

Lifetime of carbon capture and storage as a climate-change mitigation technology

Michael L. Szulczewski[a], Christopher W. MacMinn[b], Howard J. Herzog[c], and Ruben Juanes[a,d,1]

Departments of [a]Civil and Environmental Engineering and [b]Mechanical Engineering, [c]Energy Initiative, and [d]Center for Computational Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139

Edited by M. Granger Morgan, Carnegie Mellon University, Pittsburgh, PA, and approved February 15, 2012 (received for review September 19, 2011)

- ***CCS is a geologically-viable climate-change mitigation option in the United States over the next century*** (Szulczewski et al., *PNAS* 2012)

Earthquake triggering and large-scale geologic storage of carbon dioxide

Mark D. Zoback[a,1] and Steven M. Gorelick[b]

Departments of [a]Geophysics and [b]Environmental Earth System Science, Stanford University, Stanford, CA 94305

Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

- ***CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions*** (Zoback and Gorelick, *PNAS* 2012)

- Is CO_2 leakage really a show-stopping risk?

An ongoing debate …

LETTER

Juanes et al. (*PNAS* 2012)

No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful

LETTER

Zoback and Gorelick (*PNAS* 2012)

Reply to Juanes et al.: Evidence that earthquake triggering could render long-term carbon storage unsuccessful in many regions

An ongoing debate …

Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO_2 could leak

Victor Vilarrasa[a,b,1] and Jesus Carrera[c]

Vilarrasa and Carrera (*PNAS* 2015)

To prevent earthquake triggering, pressure changes due to CO_2 injection need to be limited

Zoback and Gorelick (*PNAS* 2015)

Reply to Zoback and Gorelick: Geologic carbon storage remains a safe strategy to significantly reduce CO_2 emissions

Vilarrasa and Carrera (*PNAS* 2015)

Tasks

- Task 1: Project Management, Planning and Reporting

- Task 2: Technology Status Assessment

- Task 3: Coupled modeling of flow and fault geomechanics
  1. Sequential scheme for CO_2-brine flow and geomechanics
  2. Theoretical and computational framework for flow along 2D faults
  3. Theoretical and computational framework of fault poromechanics
  4. Application to synthetic and actual geologic formations in the continental United States

- Task 4: Investigation of effects of fault rheology, pre-existing stress, and fluid pressure changes on triggered fault slip and induced seismicity
  1. Dependence of coefficient of friction on fault slip rate and state
  2. Testing of alternative descriptions of fault rheology
  3. Application to synthetic and actual formations to evaluate production scenarios and risk of induced seismicity

Tasks

- Task 5: High-resolution simulation of CO_2 migration and trapping
    1. 2D gravity currents with analogue fluids in homogeneous media
    2. Heterogeneous media
    3. 3D simulations of an analogue system
    4. High-resolution simulation of gravity currents of actual system (such as CO_2–brine system)

Increasing trend of induced earthquakes

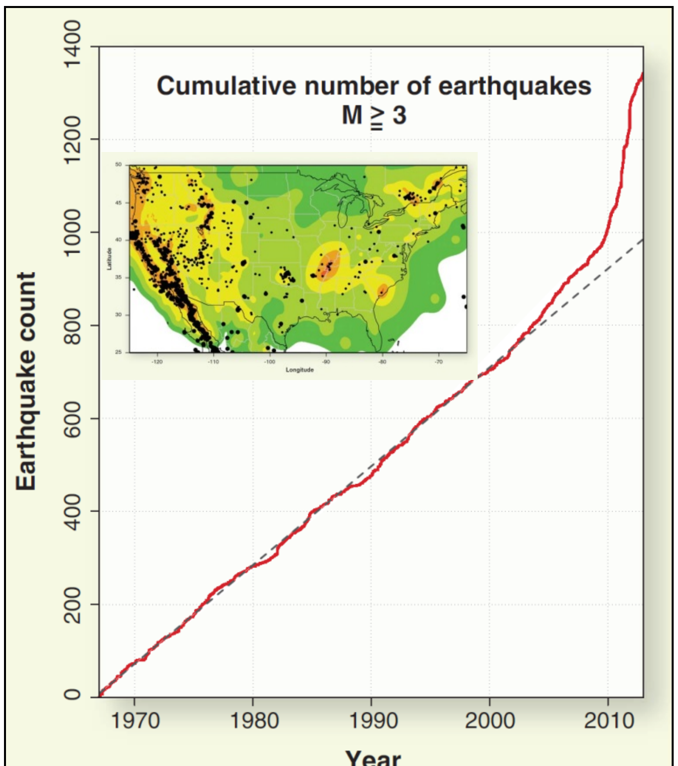
Injection-Induced Earthquakes

William L. Ellsworth

READ THE FULL ARTICLE ONLINE
http://dx.doi.org/10.1126/science.1225942

Cite this article as W. L. Ellsworth, *Science* **341**, 1225942 (2013).
DOI: 10.1126/science.1225942

Background: Human-induced earthquakes have become an important topic of political and scien discussion, owing to the concern that these events may be responsible for widespread damage an overall increase in seismicity. It has long been known that impoundment of reservoirs, surface underground mining, withdrawal of fluids and gas from the subsurface, and injection of fluids underground formations are capable of inducing earthquakes. In particular, earthquakes cause injection have become a focal point, as new drilling and well-completion technologies enable extraction of oil and gas from previously unproductive formations.



PNAS

Gas injection may have triggered earthquakes Cogdell oil field, Texas

Wei Gan[a,b] and Cliff Frohlich[b,1]

[a]School of Earth Sciences and Resources, China University of Geosciences, Beijing 10083, China; and [b]Institute for Geophysics, Jackson Sc University of Texas at Austin, Austin, TX 78758-4445

Edited by Donald W. Forsyth, Brown University, Providence, RI, and approved October 4, 2013 (received for review June 13, 2013)

www.sciencemag.org SCIENCE VOL 344 11 APRIL 2014

Human Activity May Have Triggered Fatal Italian Earthquakes, Panel Says

ROME—A pair of deadly earthquakes that struck the north of Italy in 2012 could have been triggered by the extraction of petroleum at a local oil field, according to an international panel of geoscientists.

the chair, Peter Styles of Keele University in the United Kingdom—as well as Franco Terlizzese, an engineer at Italy's Ministry of Economic Development.

In its report, dated February 2014,

Anthropogenic Seismicity Rates and Operational Parameters at the Salton Sea Geothermal Field

Emily E. Brodsky* and Lia J. Lajoie

Science **341**, 543 (2013)

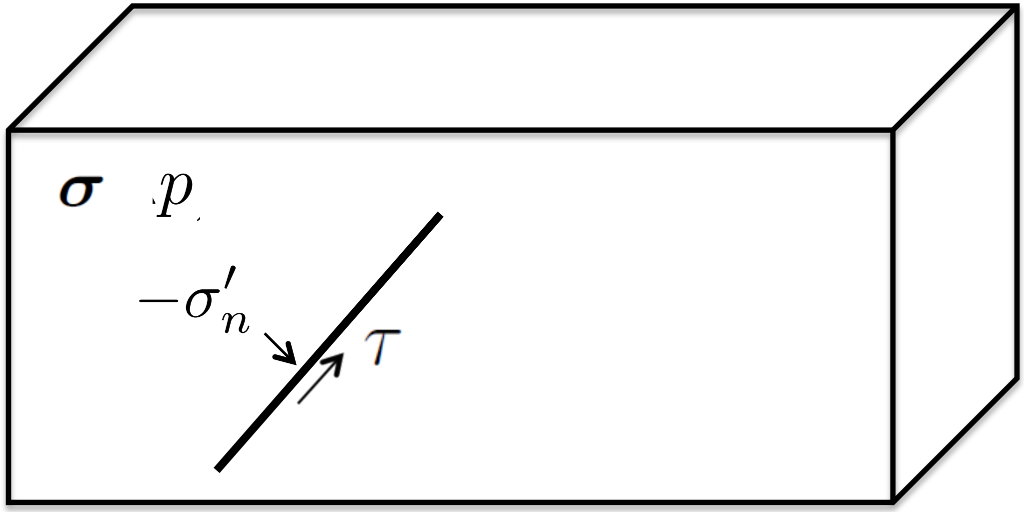
Geothermal power is a growing energy source; however, efforts to increase production are tempered by concern over induced earthquakes. Although increased seismicity commonly accompanies geothermal production, induced earthquake rate cannot currently be forecast on the basis of fluid injection volumes or any other operational parameters. We show that at the Salton Sea Geothermal Field, the total volume of fluid extracted or injected tracks the long-term evolution of seismicity. After correcting for the aftershock rate, the net fluid volume

Key questions in subsurface technologies

- How much can be extracted/stored, and at what rate?
- What is the risk of triggered/induced earthquakes?
- What is the risk of leakage?

Geomechanical modeling of faults is essential

What is the mechanism?

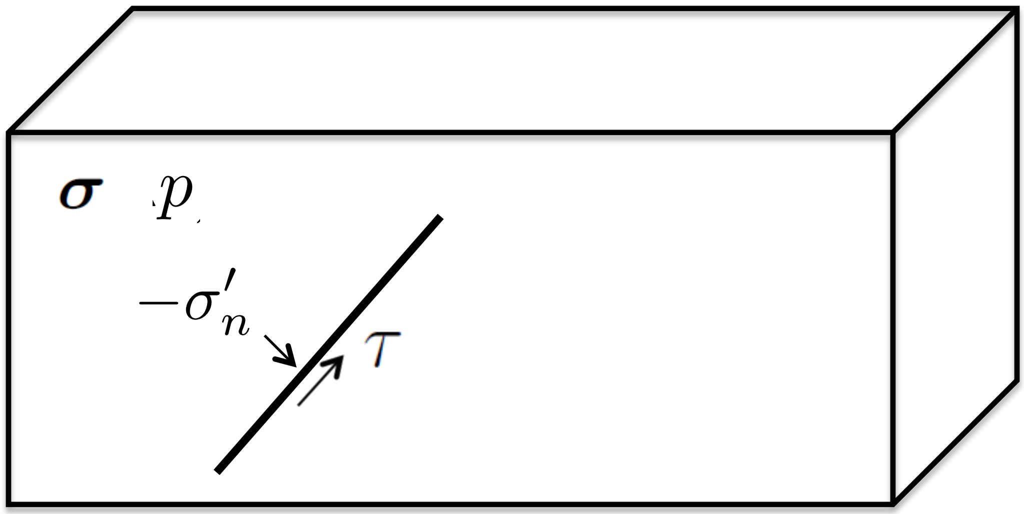


Effective stress on the fault: $(-\sigma'_n) = (-\sigma_n) - bp$

Friction shear stress: $\tau_f = \tau_0 + \mu_f(-\sigma'_n)$

Coulomb Force Function: $\mathrm{CFF} := \tau - \mu_f(-\sigma'_n)$

What is the mechanism?



Tendency to slip if: $\Delta \mathrm{CFF} = \Delta\tau - \Delta\left(\mu_f[(-\sigma_n) - bp]\right) > 0$

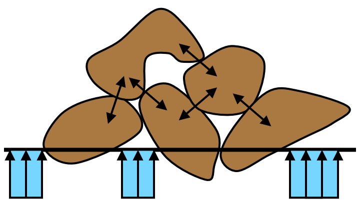
$$\Rightarrow \begin{cases} \Delta\tau > 0 & \text{(increase tectonic shear)} \\ \Delta\mu_f < 0 & \text{(fault weakening)} \\ \Delta(-\sigma_n) < 0 & \text{(poroelastic unloading)} \\ \Delta p > 0 & \text{(fluid injection)} \end{cases}$$

Multiphase poromechanics

- **Fluid mass conservation**
  - Primary unknowns: p, S

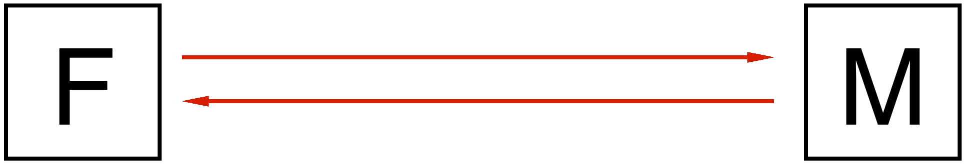
- **Linear momentum balance**
  - Primary unknown: $\boldsymbol{u}$

- **Couplings:**



$$(-\boldsymbol{\sigma}') = (-\boldsymbol{\sigma}) - bp\boldsymbol{1}$$

Effective stress

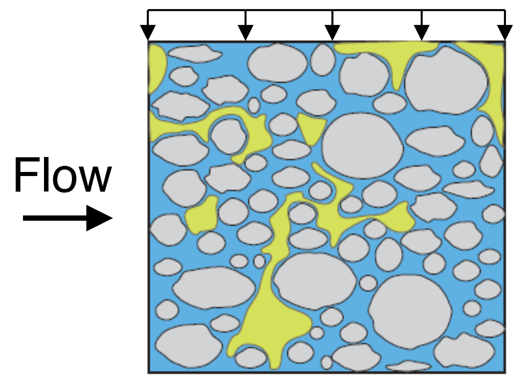


Change in volume

Change in reservoir properties: ϕ, $\boldsymbol{k}$

Biot, *JAP* 1941
Geertsma, *AIME* 1957
Rice et al, *RGSP* 1976

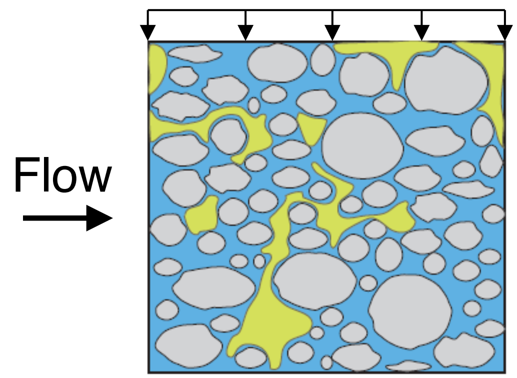
Multiphase poromechanics



Momentum balance: $\nabla \cdot \boldsymbol{\sigma} + \rho_b \boldsymbol{g} = 0$

Fluid mass balance: $\dfrac{dm_\alpha}{dt} + \nabla \cdot \boldsymbol{w}_\alpha = \rho_\alpha f_\alpha$

Multiphase poromechanics



Momentum balance: $\nabla \cdot \boldsymbol{\sigma} + \rho_b \boldsymbol{g} = 0$

Fluid mass balance: $$\frac{dm_\alpha}{dt} + \nabla \cdot \boldsymbol{w}_\alpha = \rho_\alpha f_\alpha$$

Multiphase poroelasticity: $$\left(\frac{dm}{\rho}\right)_\alpha = b_\alpha d\varepsilon_v + \sum_\beta N_{\alpha\beta} dp_\beta$$

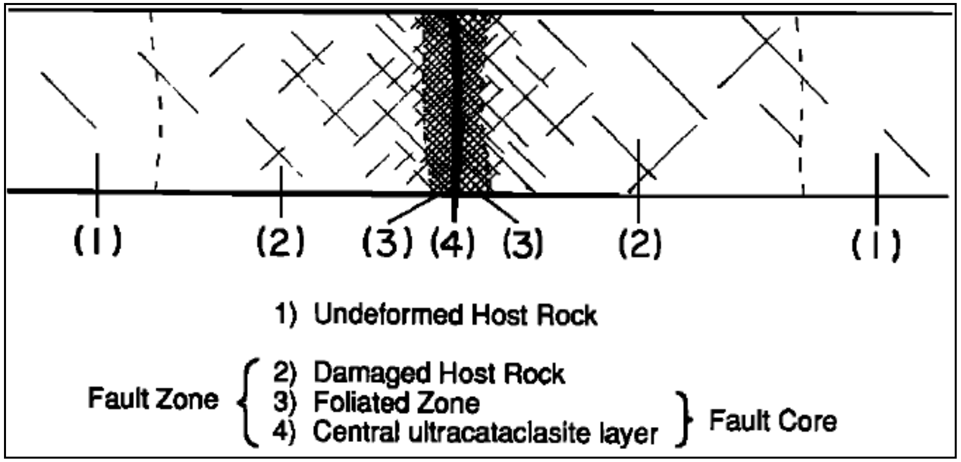
Multiphase effective stress: $\delta\boldsymbol{\sigma} = \delta\boldsymbol{\sigma}' - b\delta p_E \mathbf{1}, \quad \delta\boldsymbol{\sigma}' = \boldsymbol{C}_{dr} : \boldsymbol{\varepsilon}$

Coussy, 1995; Kim et al., *SPE J.* 2013

Earthquakes happen due to rupture of a fault

Interpretation of a fault – *Structural*

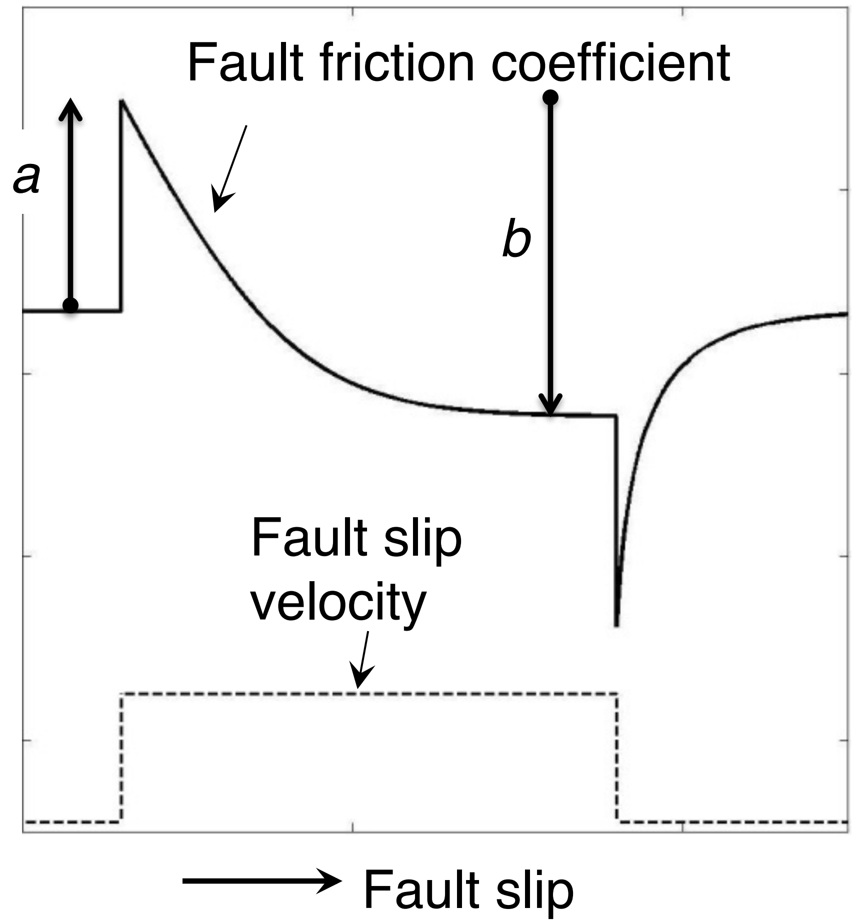
surface of discontinuity



Chester et al, *JGR* 1993
Anderson, *Tectonophys.* 1983
Marone, *Ann. Rev. EPS*, 1998

Interpretation of a fault – *Functional*

Rate and state friction model



$$\tau_f = \tau_0 + \mu_f(-\sigma'_n)$$

Fault friction coefficient

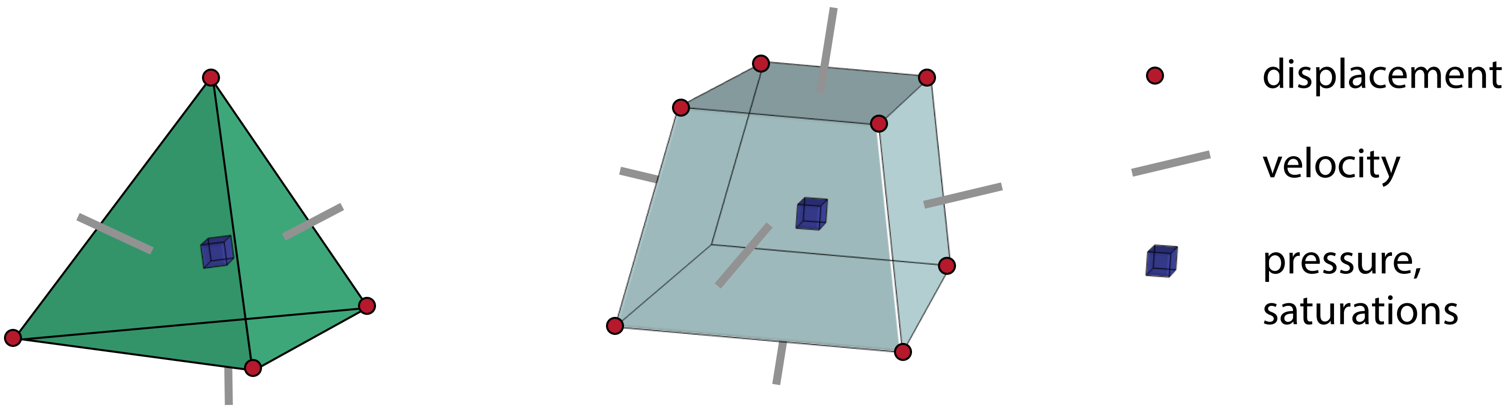
Fault friction and strength evolve dynamically

- (a-b) > 0 : velocity strengthening; stable slip
- (a-b) < 0 : velocity weakening; runaway slip; potential for earthquake

Marone, *Ann. Rev. EPS*, 1998

Computational modeling of flow-geomechanics

- **Discretization** (Jha and Juanes, *Acta Geotech.* 2007)
  - Finite elements for mechanics; finite volumes for flow
  - Stable, convergent scheme
  - Single, unstructured computational grid

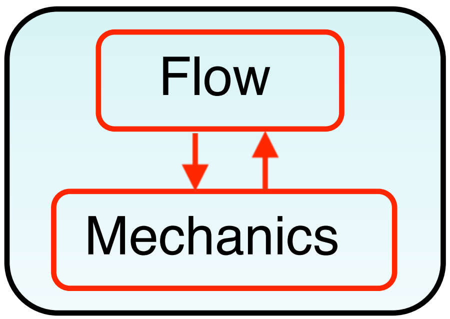


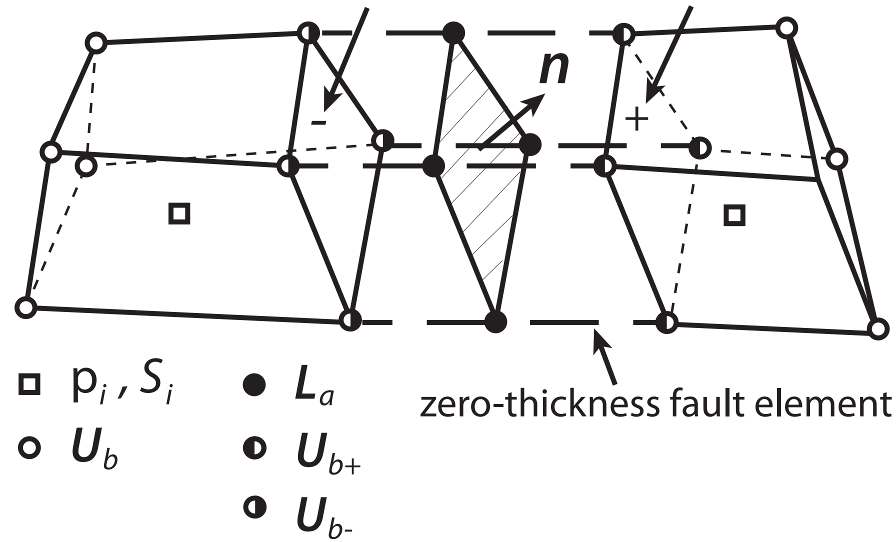
- **Coupling strategies** (Kim, Tchelepi and Juanes, *SPE J.* 2011; *CMAME* 2011a,b; *SPE J.* 2013)
  - Fixed-stress operator split
  - Efficient, unconditionally stable sequential scheme
  - Recently, generalized to a class of iterative schemes

    (Castelleto, White, et al., *IJNAMG* 2015, *CMAME* 2015)

Coupled fluid flow and geomechanics simulator

Jha and Juanes, *Water Resour. Res.*, 2014

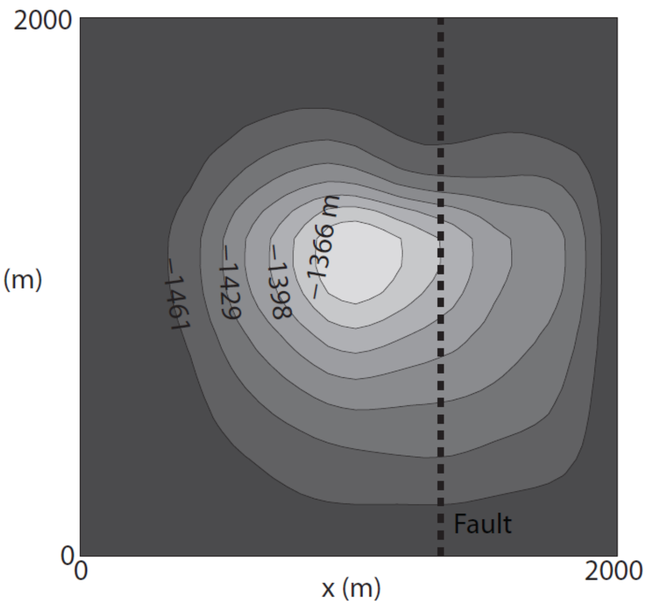


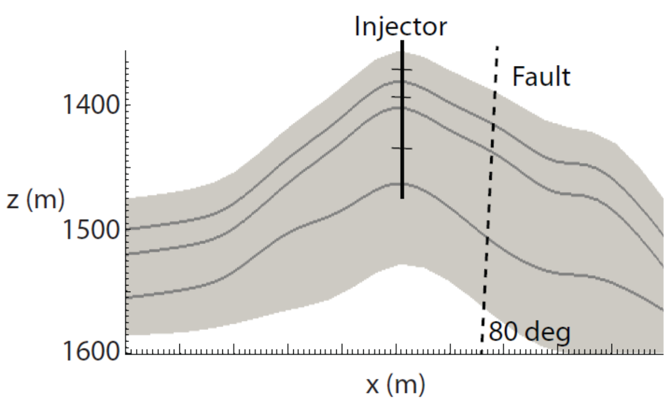


- Features of the coupled code:
  - Finite element geomechanics code (PyLith)
  - Finite volume multiphase-flow reservoir simulator (GPRS)
  - ***Sophisticated formulation for fault deformation and slip***
  - C++, fast, parallel
  - Uses hexahedral or tetrahedral grid
  - Viscoelastic and elastoplastic rheology; rate- and state- fault friction

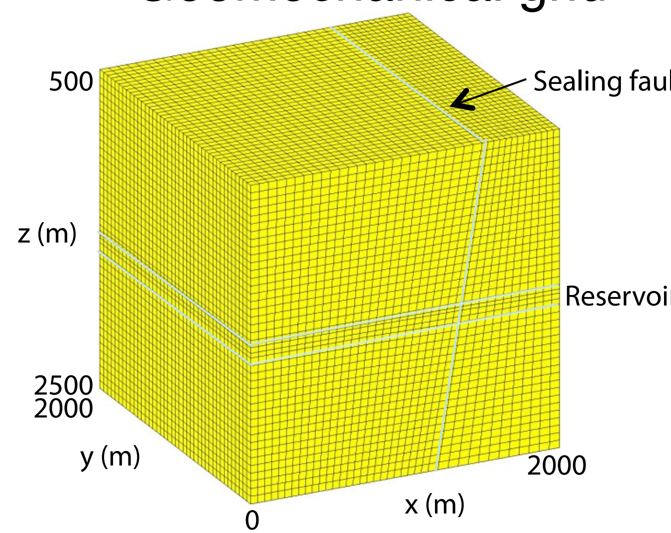
Synthetic case: faulting induced by CO_2 injection

Dome-shaped aquifer

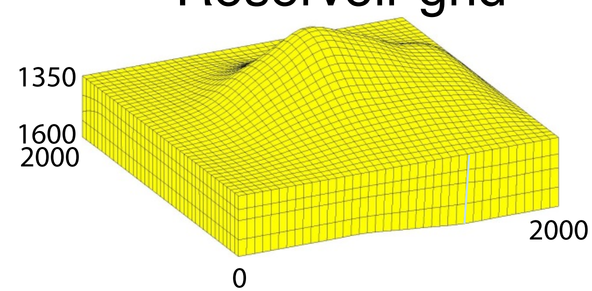




Geomechanical grid



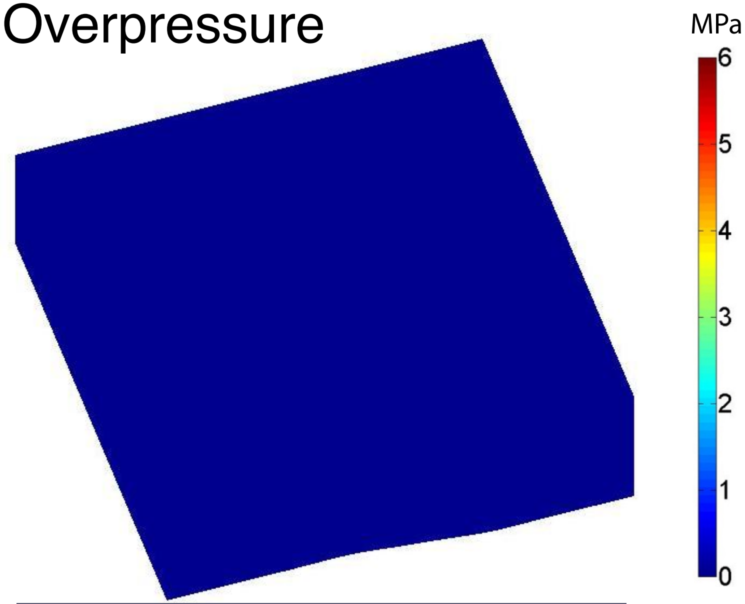
Reservoir grid



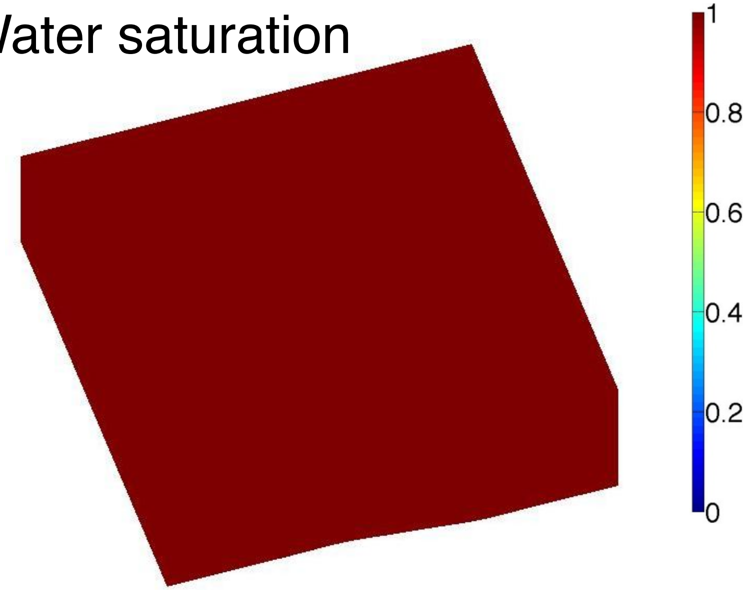
- Normal faulting regime
- Rate- and State- friction law: *a* = 0.002, *b* = 0.08, critical slip = 1 cm

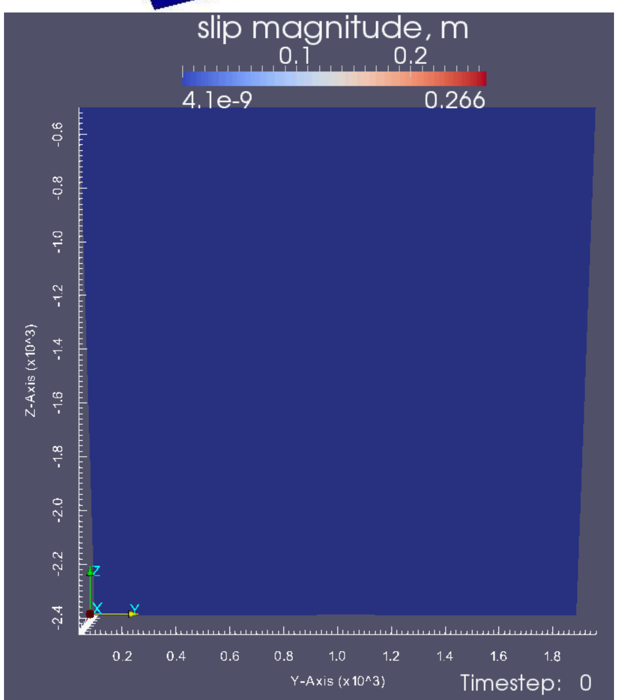
Fault slip due to over-pressurization

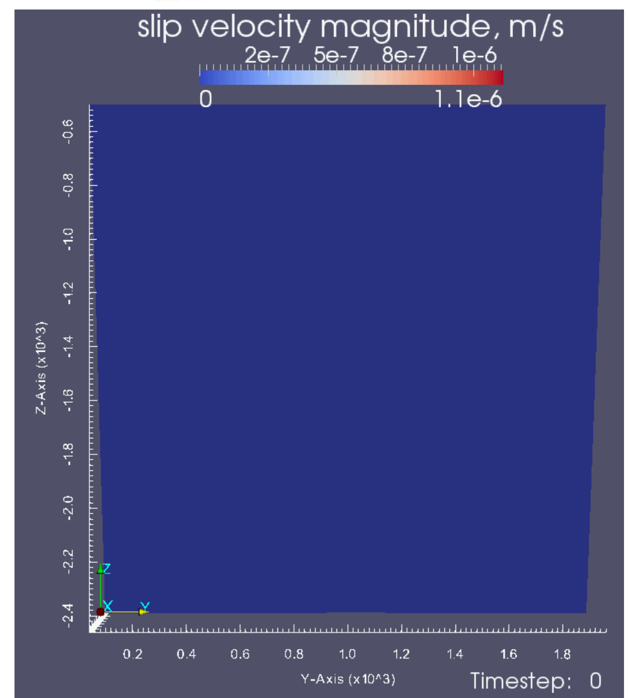
Overpressure



Water saturation







AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2013WR015175

Key Points:

- New computational approach to coupled multiphase flow and geomechanics
- Faults are represented as surfaces, capable of simulating runaway slip
- Unconditionally stable sequential solution of the fully coupled

Coupled multiphase flow and poromechanics: A computational model of pore pressure effects on fault slip and earthquake triggering

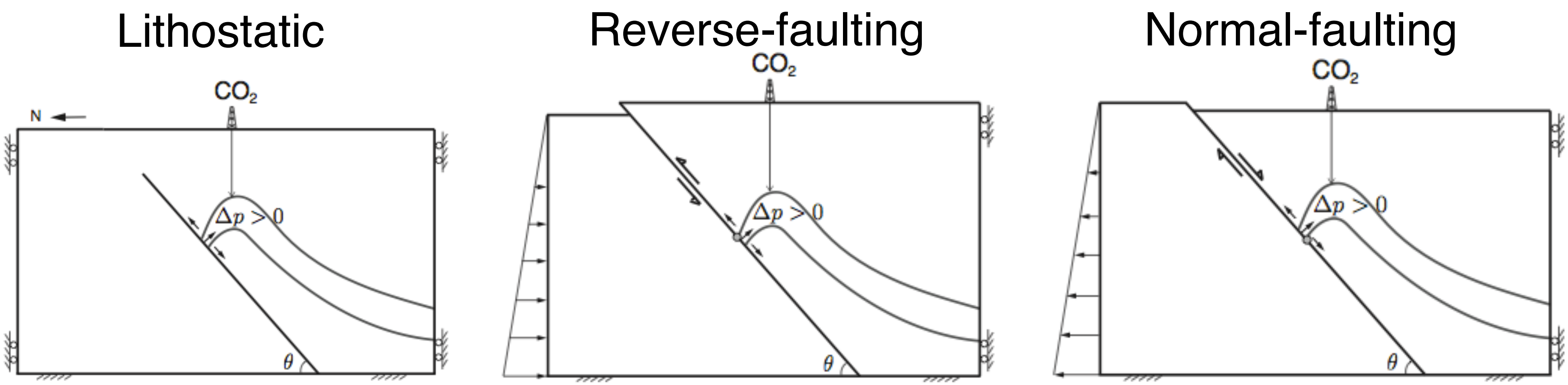
Birendra Jha[1] and Ruben Juanes[1]

[1]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Effect of tectonic stress on fault stability

Tectonic regime

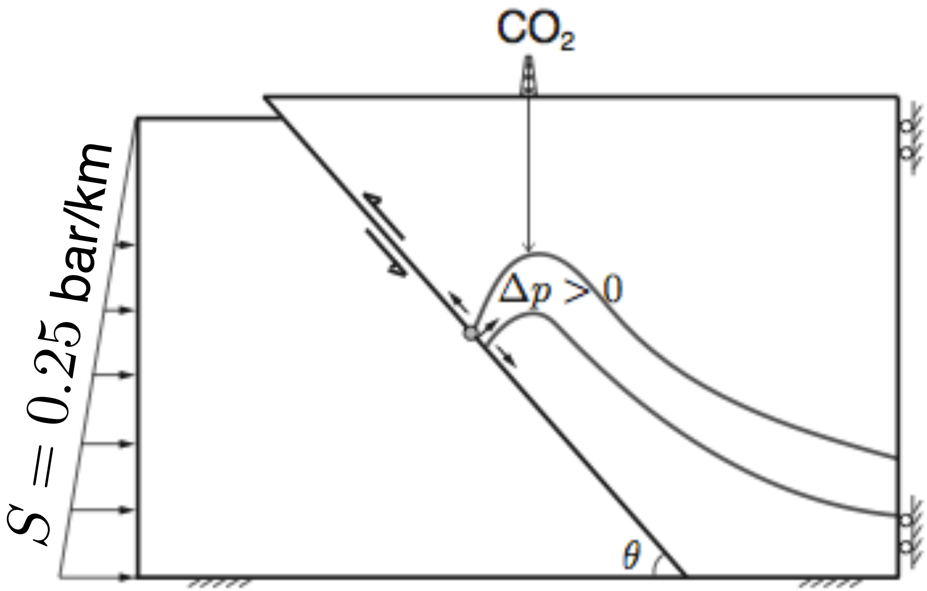
- ❑ determines preferred failure mode
- ❑ interacts with injection-induced stress changes to control onset and magnitude of seismicity



Question:

- What is the best injection strategy in a given tectonic regime? For example, is CO_2 injection with brine production a safe strategy in reverse-faulting regime?

Isolate tectonic contribution from injection-induced perturbation



At a point at depth z km,

$$\boldsymbol{\sigma} = (0, -zS, 0)$$

$$\boldsymbol{T} = \boldsymbol{\sigma}\boldsymbol{n} = [0, zS\sin\theta, 0]$$

$$\Delta\sigma_n^{\text{tec}} = \boldsymbol{T}\cdot\boldsymbol{n} = -zS\sin^2\theta$$

$$\Delta\boldsymbol{\tau}^{\text{tec}} = [0, zS\sin\theta\cos^2\theta, zS\sin^2\theta\cos\theta]$$

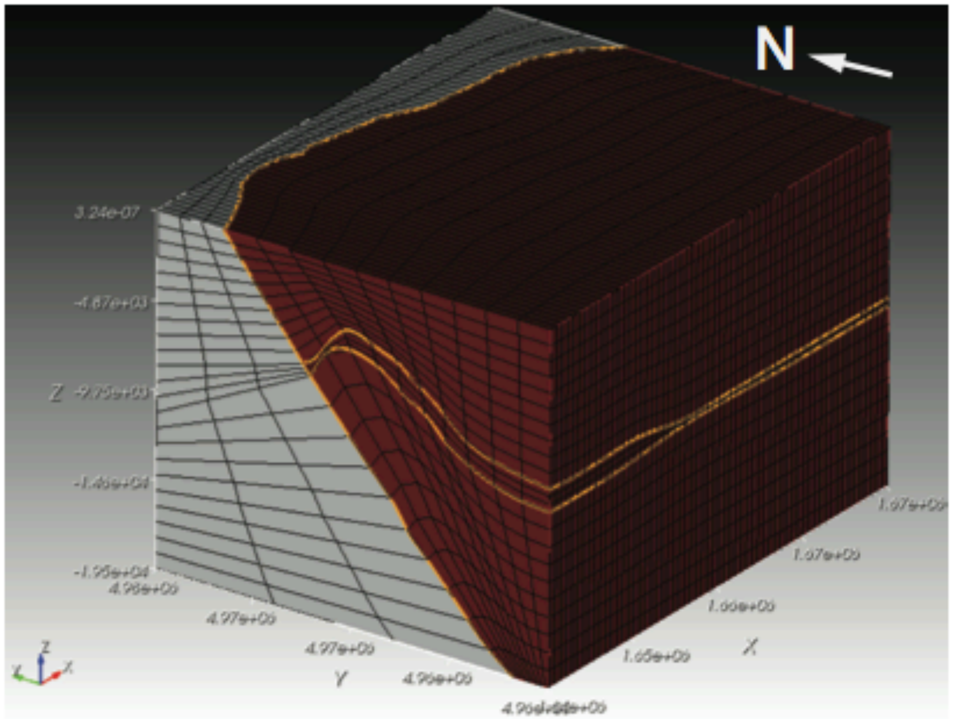
$$\begin{aligned}\Delta\text{CFF} &= [\Delta\tau + \mu_f\Delta\sigma_n]^{\text{tec}} + [\Delta\tau + \mu_f(\Delta\sigma_n + b\Delta p)]^{\text{ind}} \\ &= \Delta\text{CFF}^{\text{tec}} + \Delta\text{CFF}^{\text{ind}}\end{aligned}$$

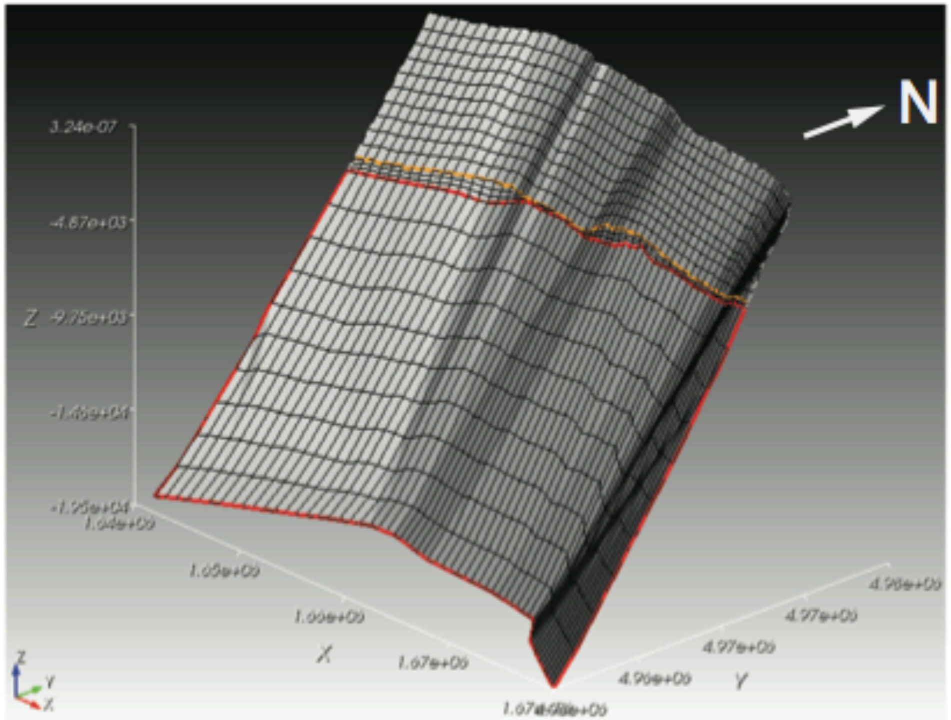
Increase in Coulomb stress with depth,

$$\Delta\text{CFF}^{\text{tec}}/z = S\sin\theta(\cos\theta - \mu_f\sin\theta)$$

A case study: CO_2 injection in a reservoir

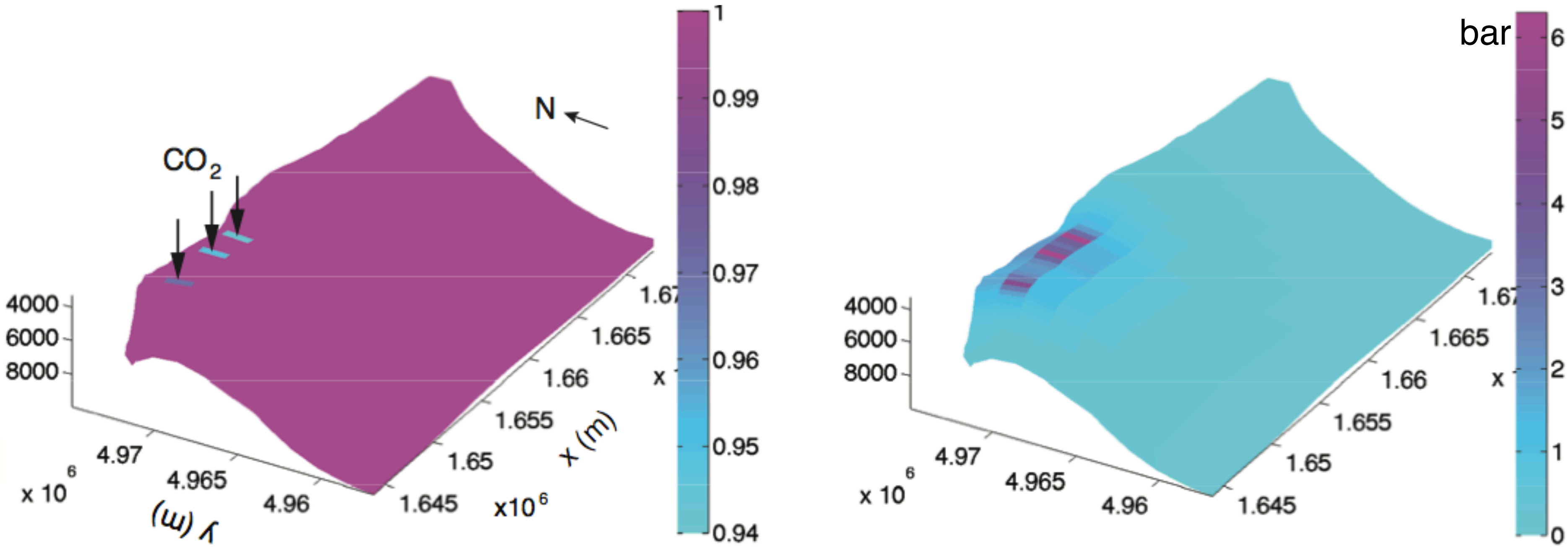
- 3D model of a depleted oilfield in an anticline with a bounding fault
- Injection for 20 years under three different stress regimes





Coupled flow and geomechanical modeling

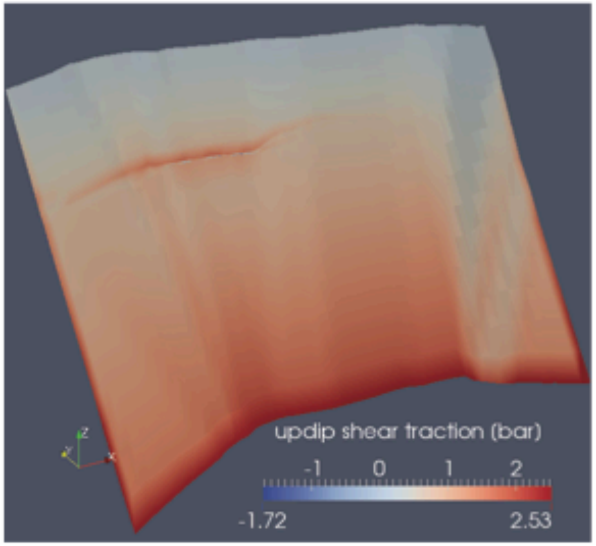
- CO_2 accumulates near the top of the anticline (left figure) pressurizing the reservoir (right)



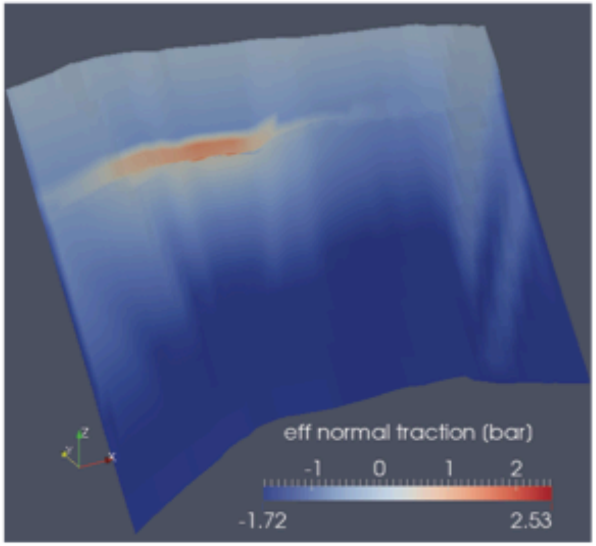
Fault stability in reverse-faulting regime

- Shear increases due to reservoir expansion.
- Fault unclamps due to pressure-induced drop in effective compressive stress

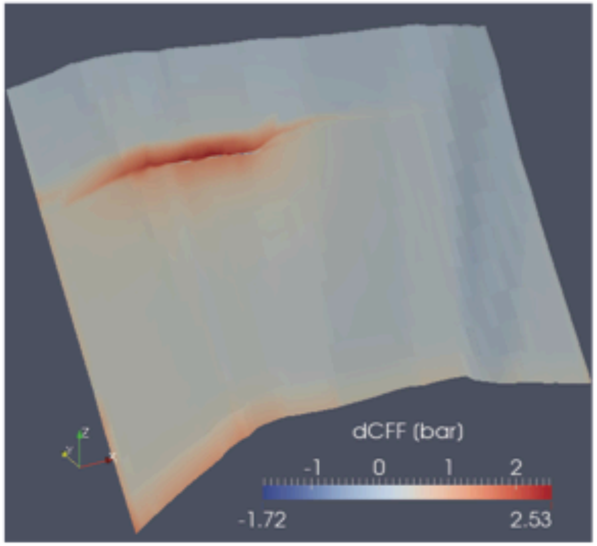
Up-dip shear



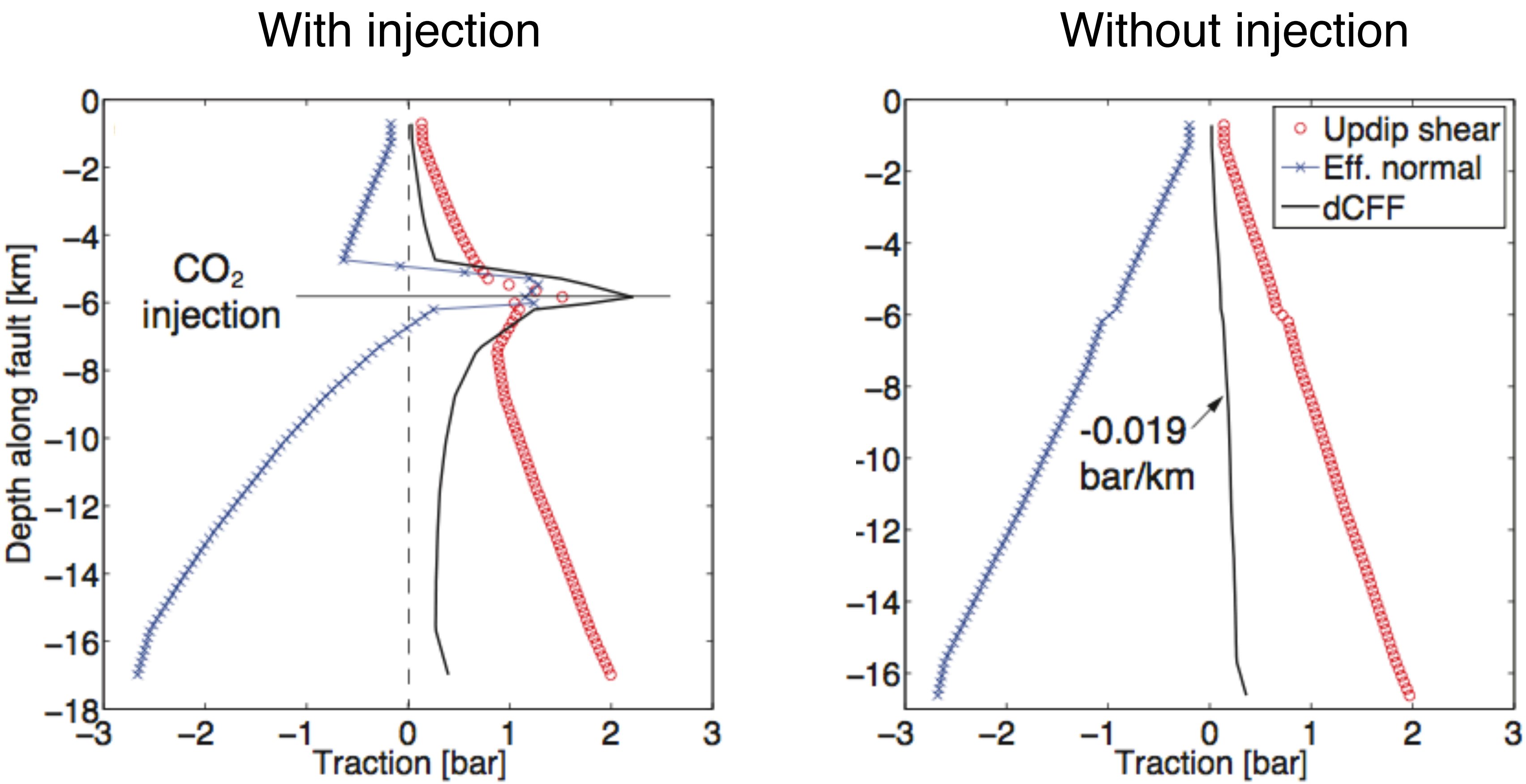
Effective normal



Coulomb stress



Tectonic contribution to failure in reverse-faulting regime

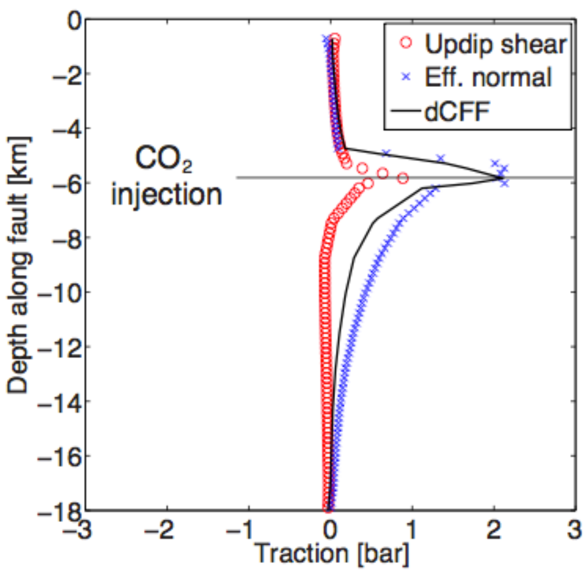


$$\Delta\mathrm{CFF}^{\mathrm{tec}}/z = S\sin\theta(\cos\theta - \mu_f \sin\theta)$$
$$= -0.019\,\mathrm{bar/km}$$

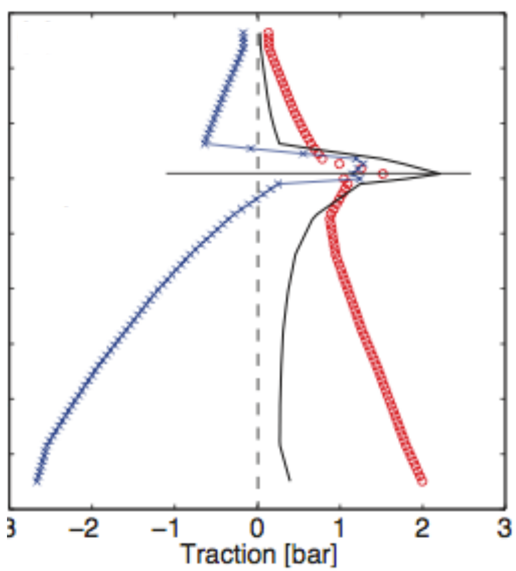
Conclusions

- Size of destabilized region depends on tectonic regime
- Traction-dependent changes in fault permeability, relevant for leakage, varies with tectonic regime

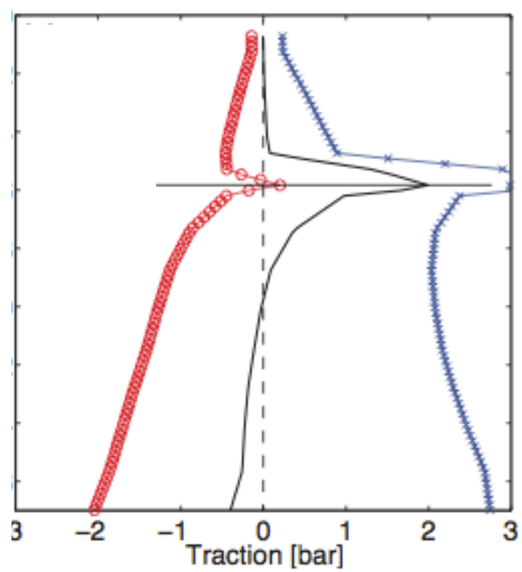
Lithostatic



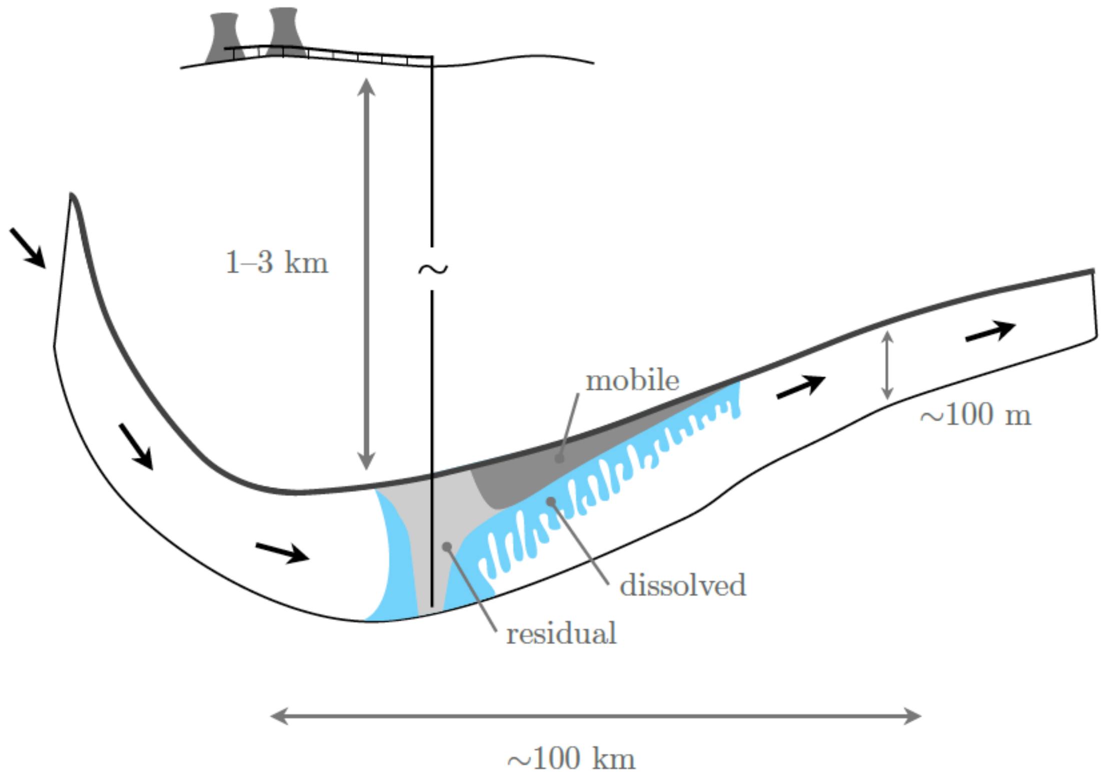
Reverse-faulting



Normal-faulting



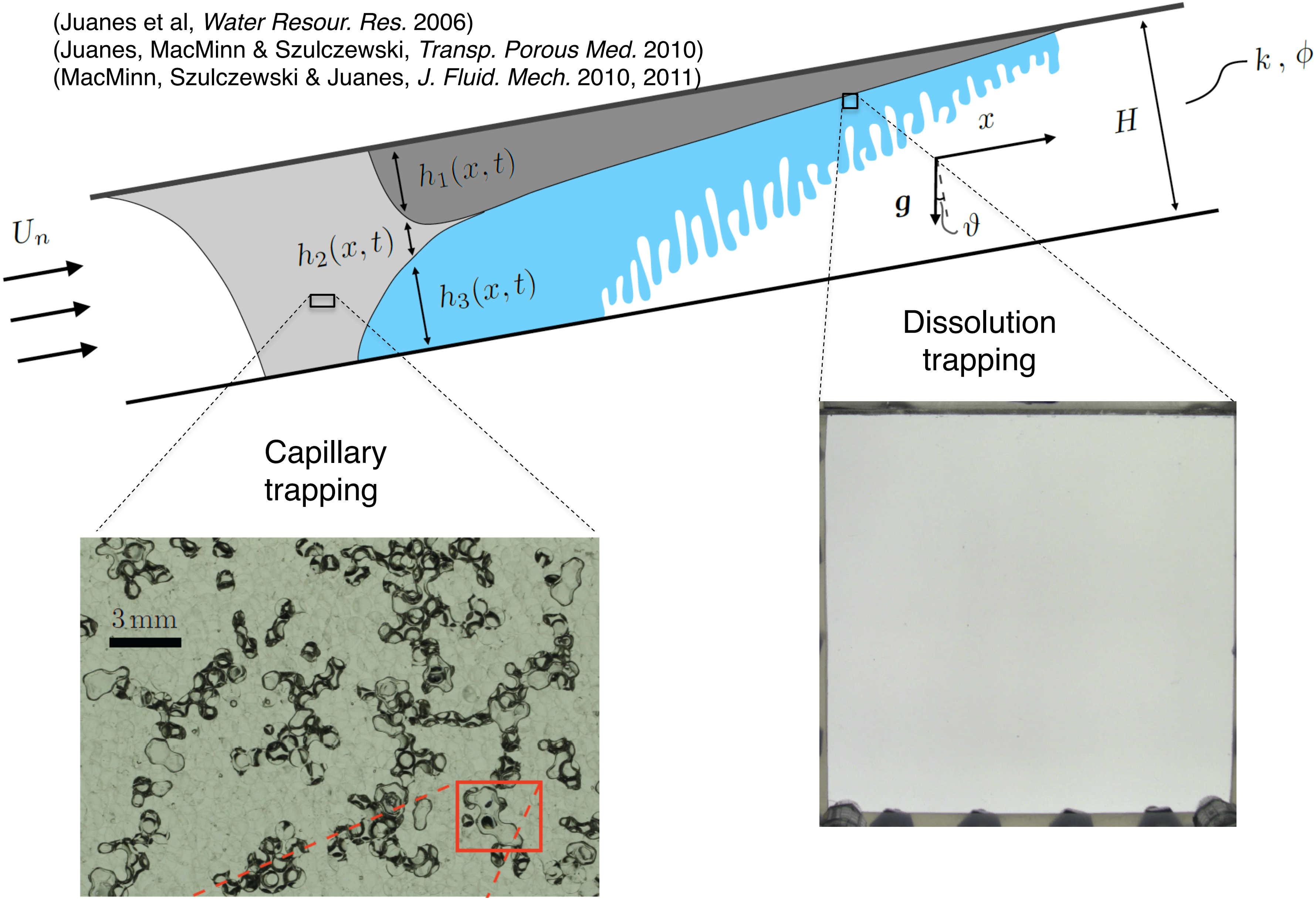
Storage must be understood at the scale of entire geologic basins



- **Two constraints**
  - The footprint of the migrating CO_2 plume must fit in the basin
  - The pressure induced by injection must not fracture the rock

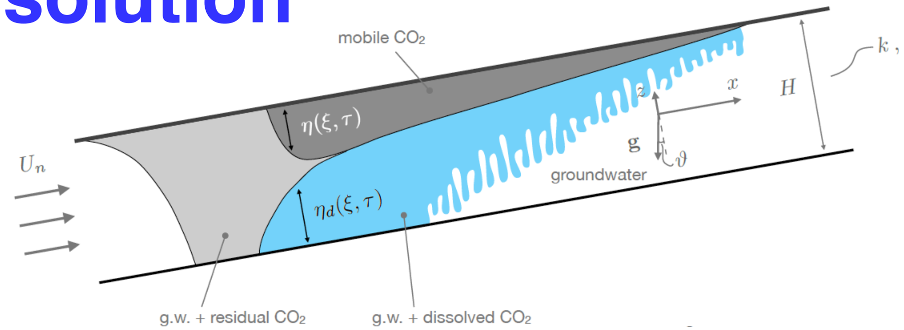
Trapping mechanisms

(Juanes et al, *Water Resour. Res.* 2006)
(Juanes, MacMinn & Szulczewski, *Transp. Porous Med.* 2010)
(MacMinn, Szulczewski & Juanes, *J. Fluid. Mech.* 2010, 2011)



Plume migration with dissolution

(Juanes, MacMinn & Szulczewski, *Transp. Porous Med.* 2010)
(MacMinn, Szulczewski & Juanes, *J. Fluid. Mech.* 2010, 2011)

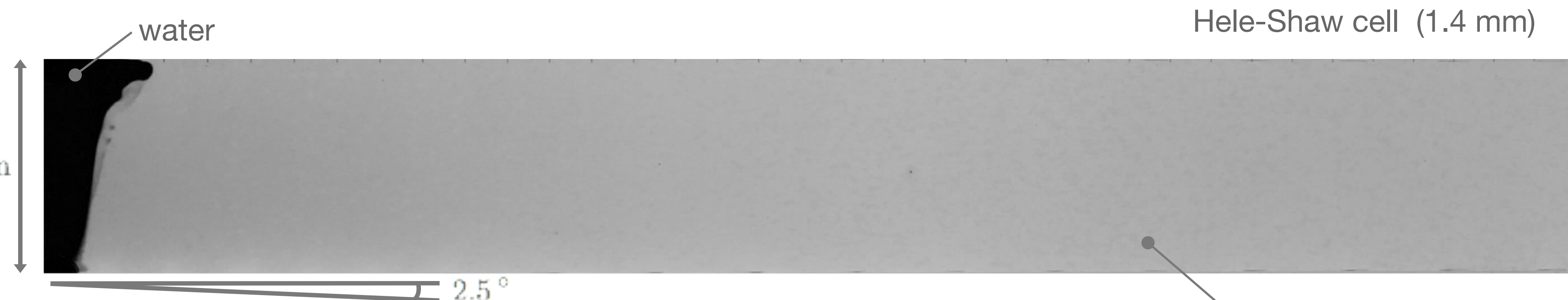


❑ Theory

advective | diffusive | sink

$$\underbrace{\tilde{\mathcal{R}}}_{\text{residual trapping}} \frac{\partial \eta}{\partial \tau} + \boxed{\underbrace{N_f \frac{\partial f}{\partial \xi}}_{\text{flow}} + \underbrace{N_s \frac{\partial}{\partial \xi}\Big[(1-f)\,\eta\Big]}_{\text{slope}}} - \boxed{\underbrace{N_g \frac{\partial}{\partial \xi}\left[(1-f)\,\eta\,\frac{\partial \eta}{\partial \xi}\right]}_{\text{spreading}}} = \boxed{\underbrace{-\tilde{\mathcal{R}}\,N_d}_{\text{dissolution}}}$$

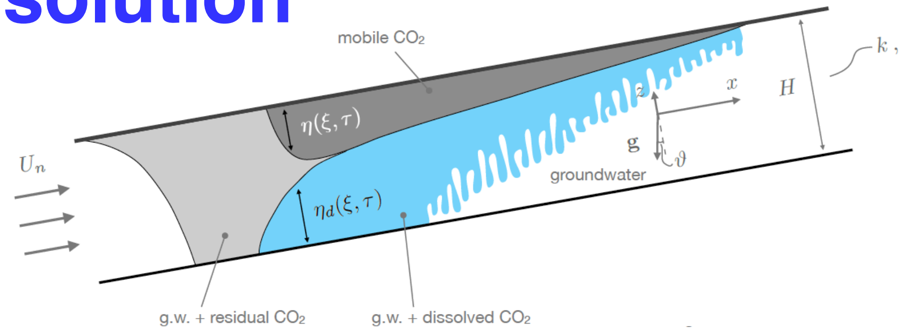
❑ Experiments



(MacMinn & Juanes, *Geophys. Res. Lett.*, 2013)

Plume migration with dissolution

(Juanes, MacMinn & Szulczewski, *Transp. Porous Med.* 2010)
(MacMinn, Szulczewski & Juanes, *J. Fluid. Mech.* 2010, 2011)



- Theory

$$\underbrace{\tilde{\mathcal{R}}}_{\text{residual trapping}}\frac{\partial\eta}{\partial\tau} + \overbrace{\boxed{\underbrace{N_f \frac{\partial f}{\partial\xi}}_{\text{flow}} + \underbrace{N_s\frac{\partial}{\partial\xi}\left[(1-f)\,\eta\right]}_{\text{slope}}}}^{\text{advective}} - \overbrace{\boxed{\underbrace{N_g \frac{\partial}{\partial\xi}\left[(1-f)\,\eta\,\frac{\partial\eta}{\partial\xi}\right]}_{\text{spreading}}}}^{\text{diffusive}} = \overbrace{\boxed{\underbrace{-\tilde{\mathcal{R}}\,N_d}_{\text{dissolution}}}}^{\text{sink}}$$

- Experiments

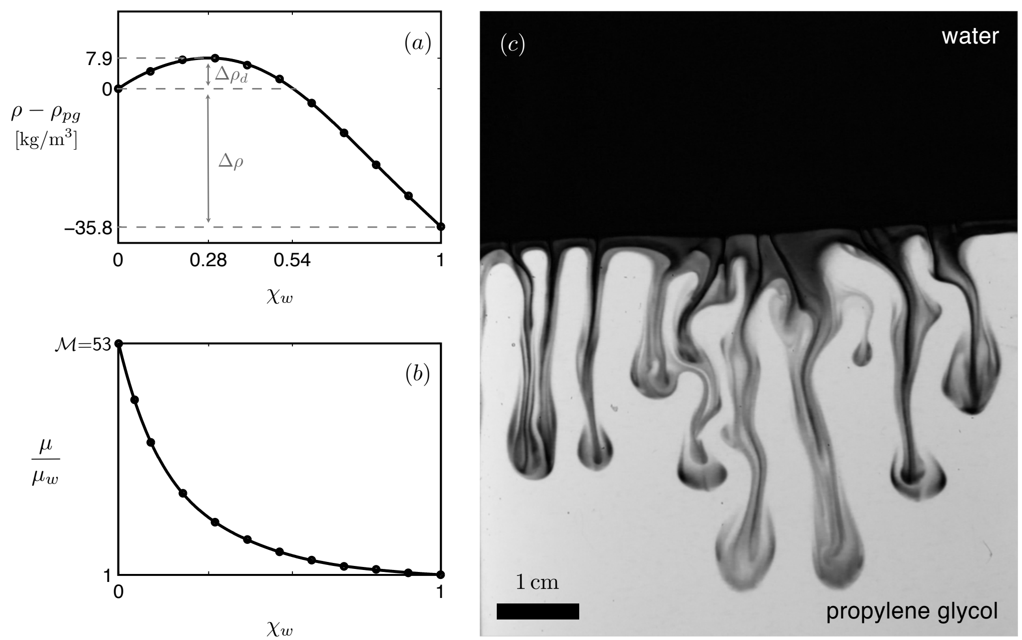
(MacMinn & Juanes, *Geophys. Res. Lett.*, 2013)

Dissolution by convective mixing

- Dimensionless governing equations

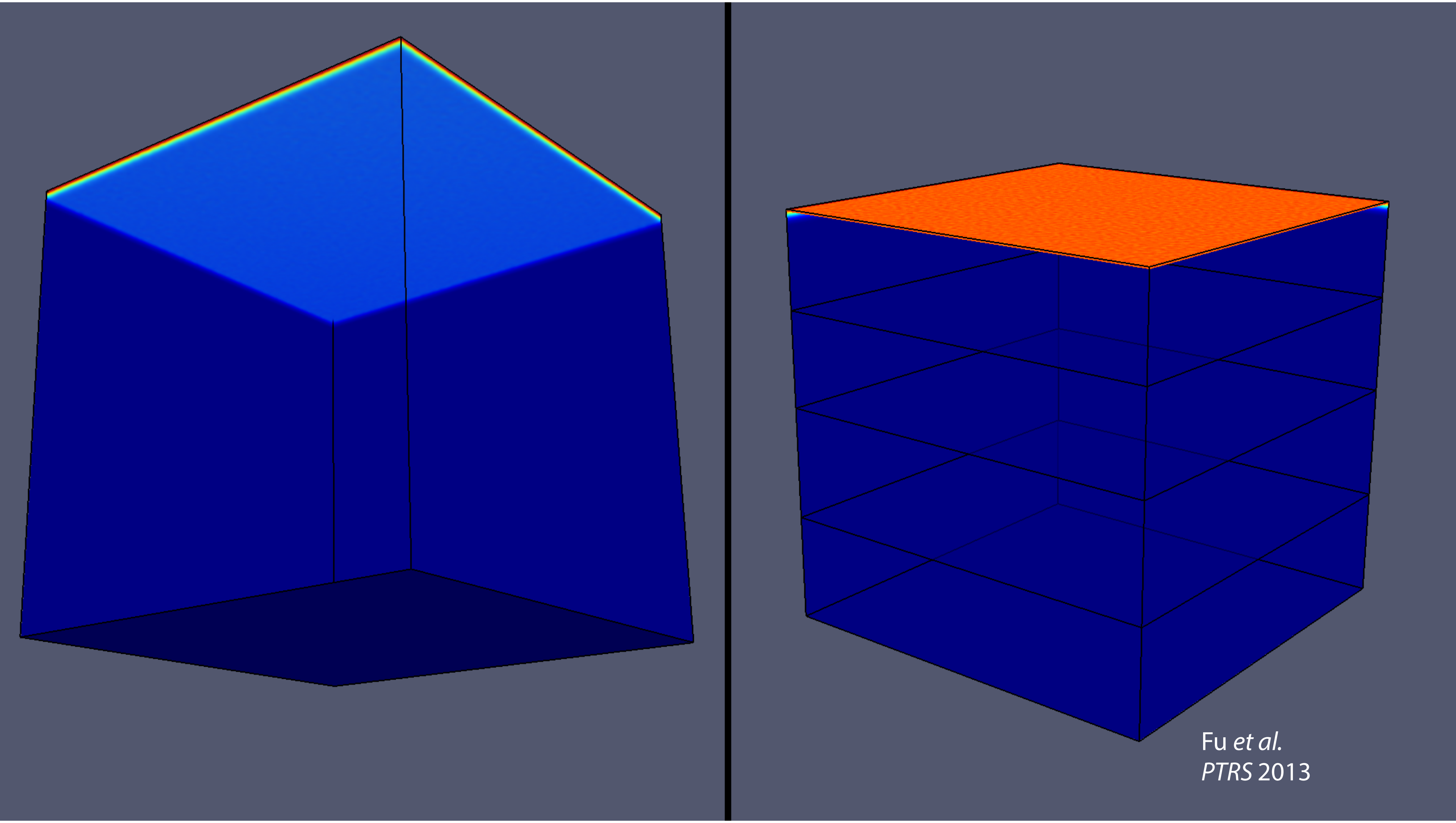
$$\nabla \cdot \boldsymbol{u} = 0; \quad \boldsymbol{u} = -(\nabla p - c\nabla z),$$

$$\partial_t c + \nabla \cdot \left(\boldsymbol{u}c - \frac{1}{\mathrm{Ra}} \nabla c \right) = 0,$$

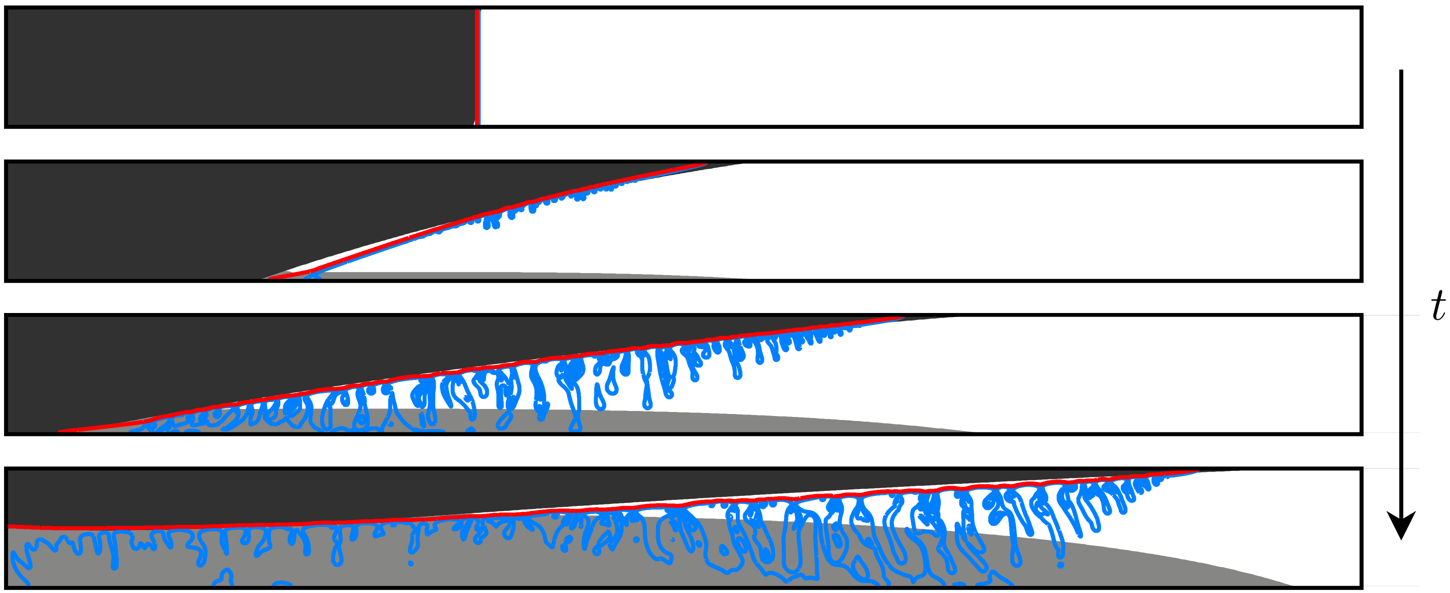


(Hidalgo et al., *Phys. Rev. Lett.,* 2012)

Dissolution by convective mixing

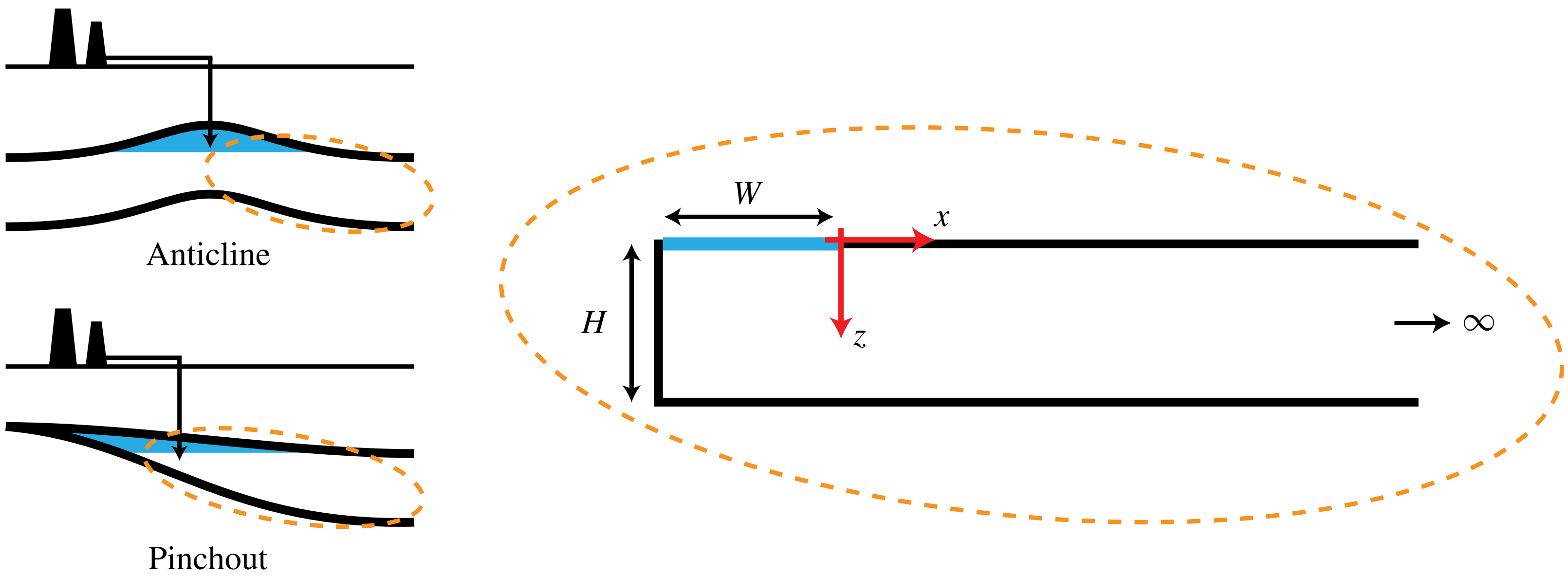


Plume migration with dissolution

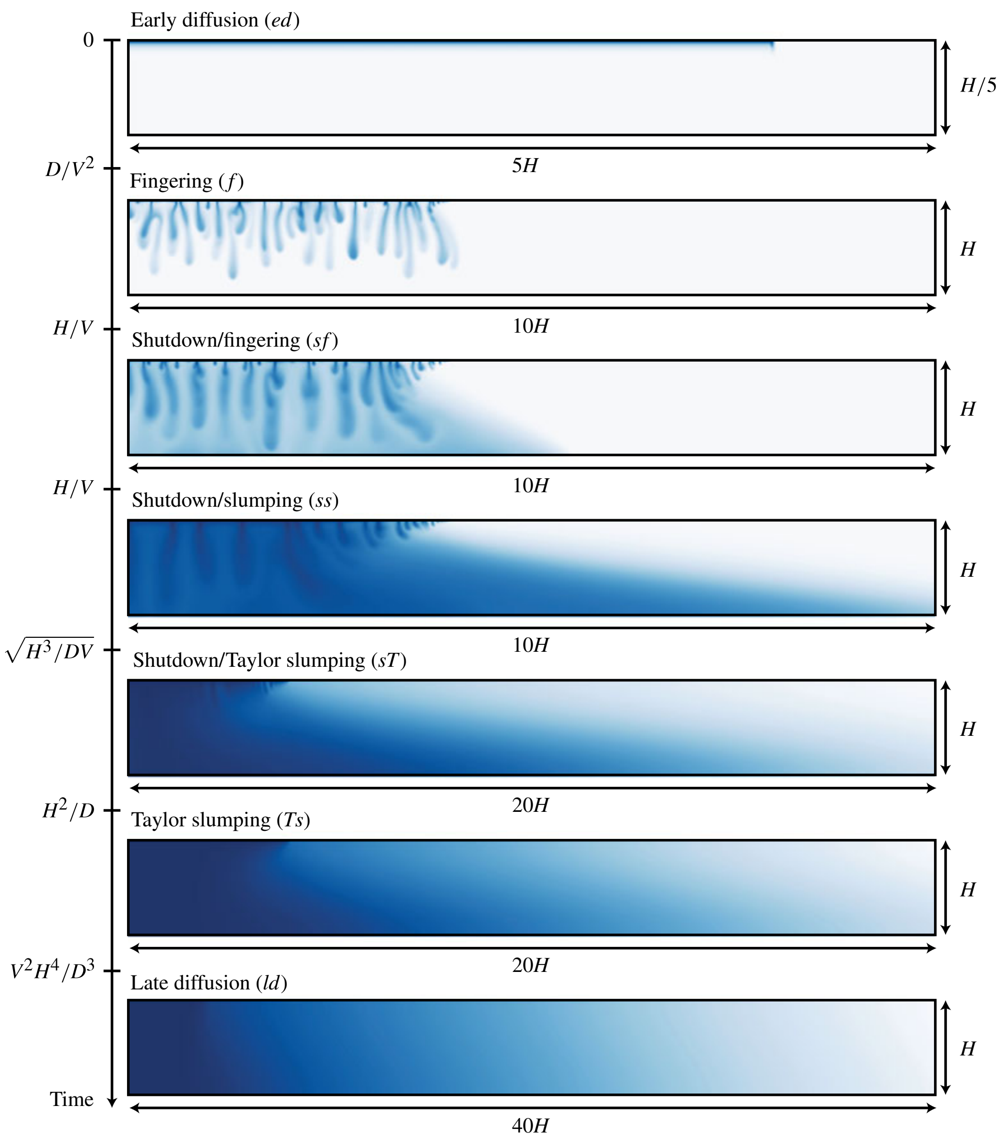


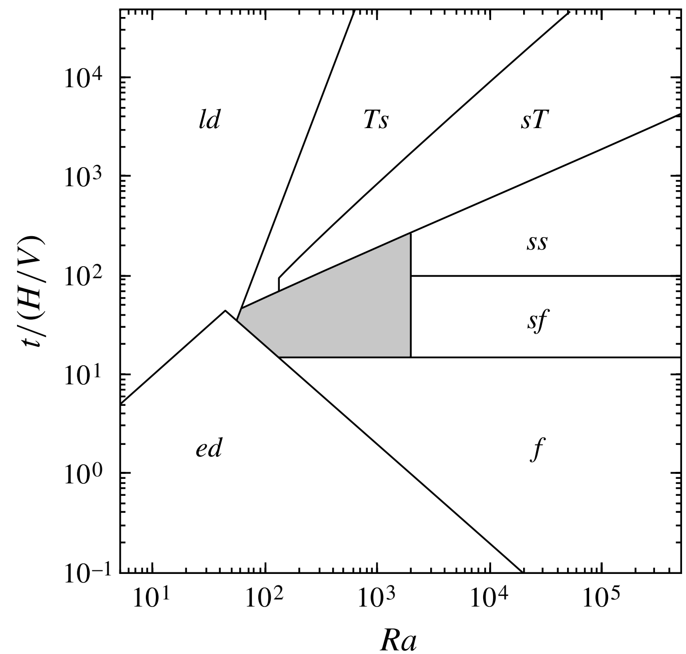
(Hidalgo, MacMinn & Juanes, *Adv. Water Resour.*, 2013)

CO2 dissolution in structural traps



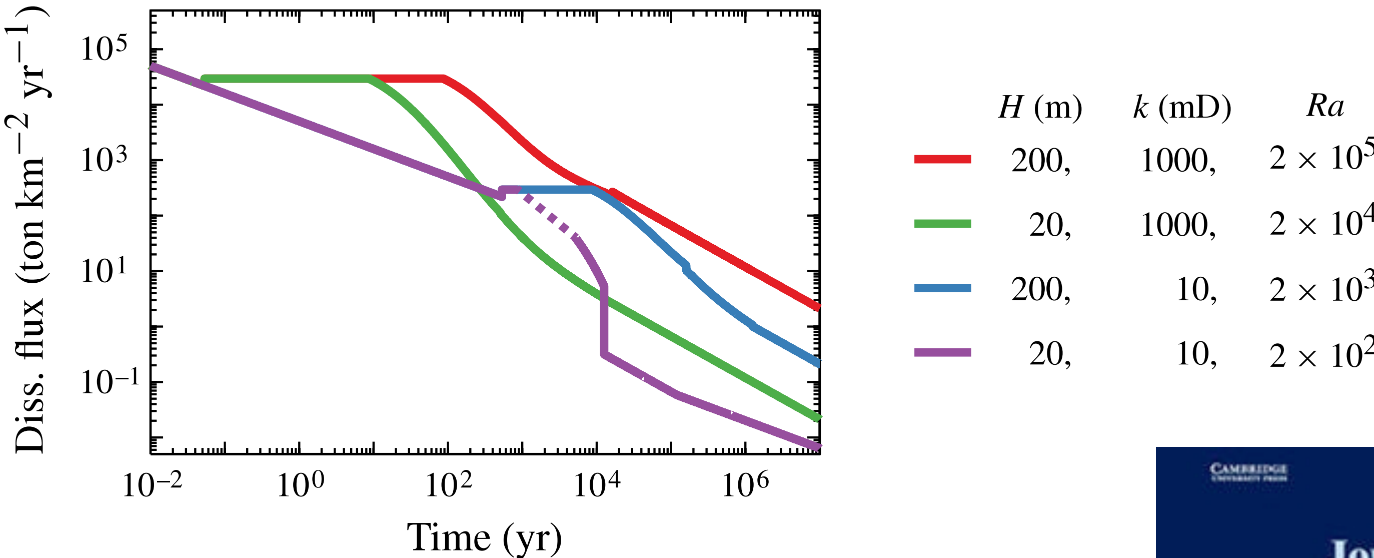
CO2 dissolution in structural traps



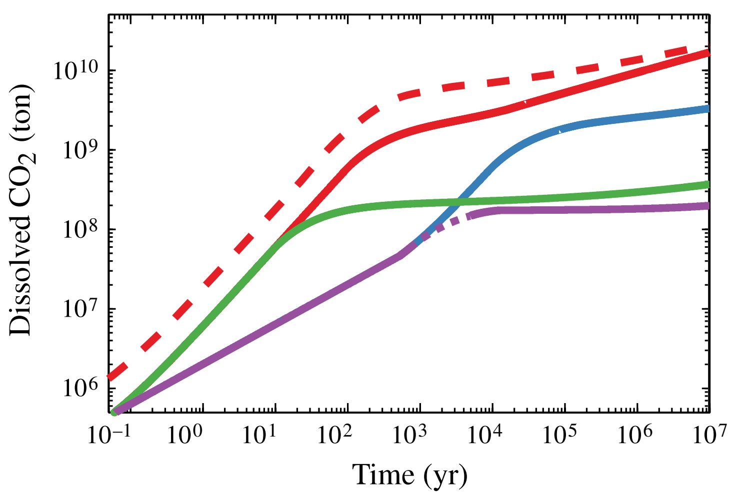


CO2 dissolution in structural traps

- Dissolution flux



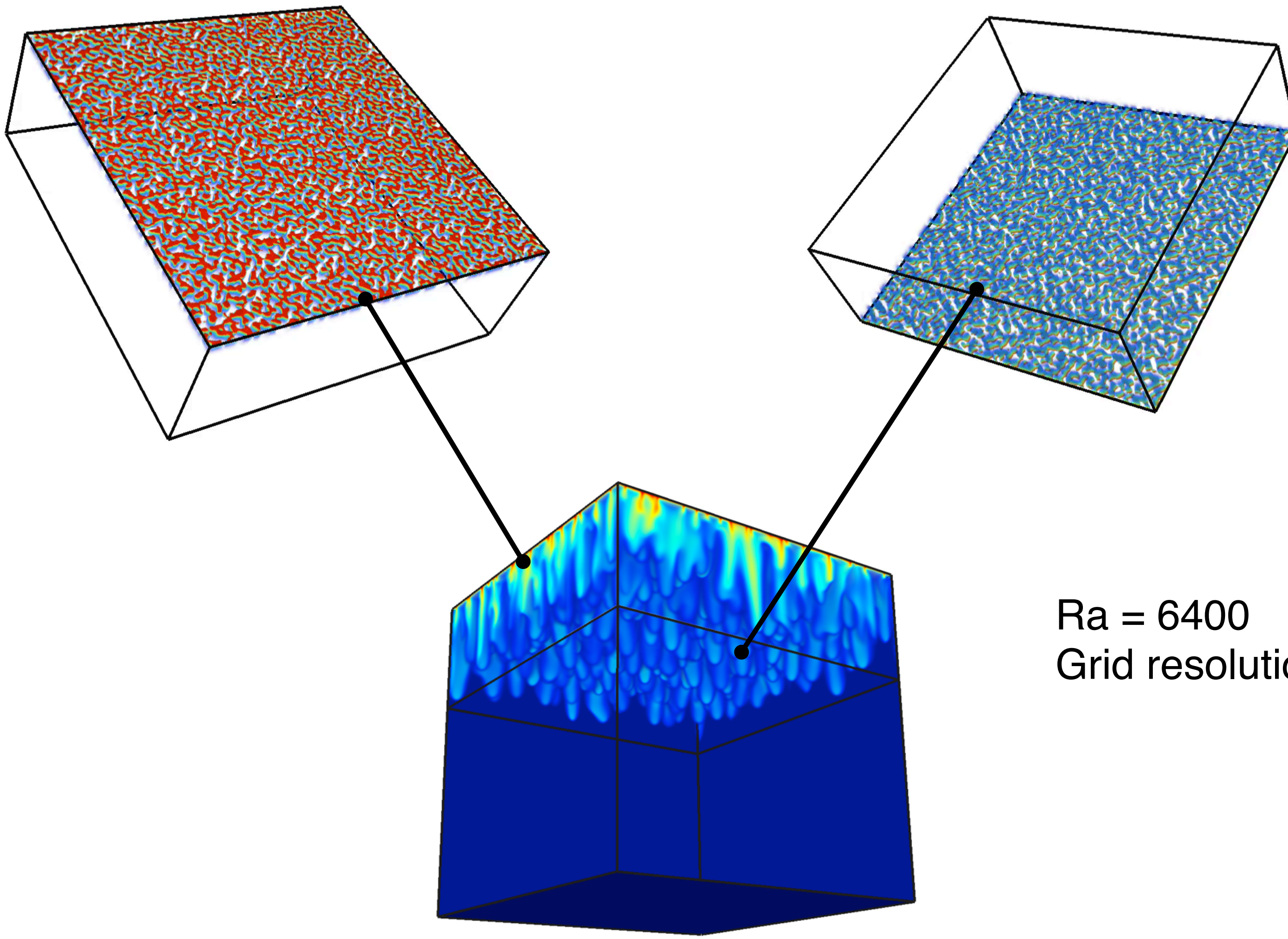
- Cumulative dissolution mass



(Szulczewski, Hesse & Juanes, *J. Fluid Mech.*, 2013)

Coarsening dynamic of CO2 rich fingers

Recall 3D dynamics of CO2 convective mixing



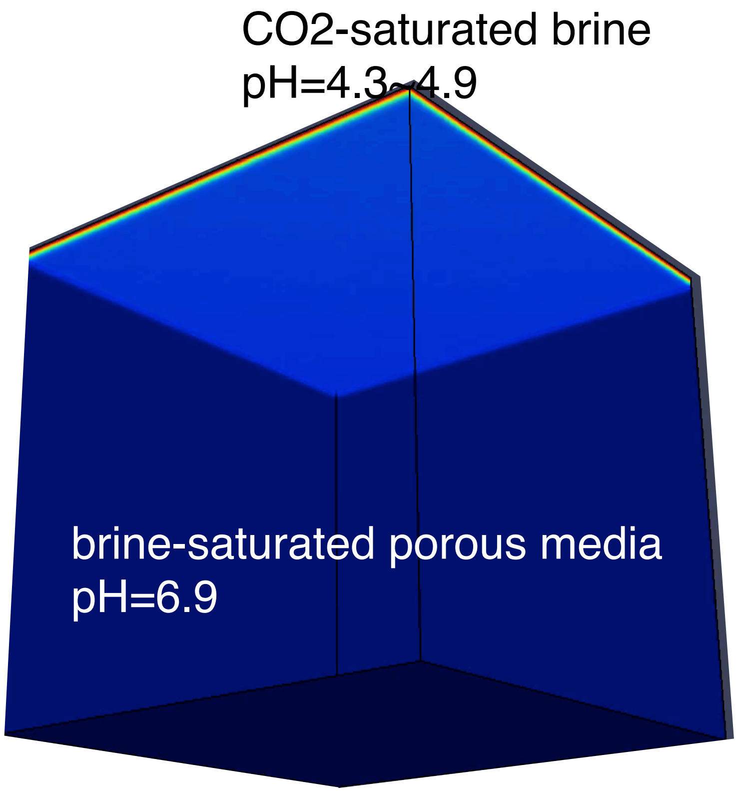
Ra = 6400
Grid resolution: 512^3

Fu, Cueto-Felgueroso & Juanes (*Phil. Trans. R. Soc. A.* 2013)

Rock dissolution from CO2 convective mixing

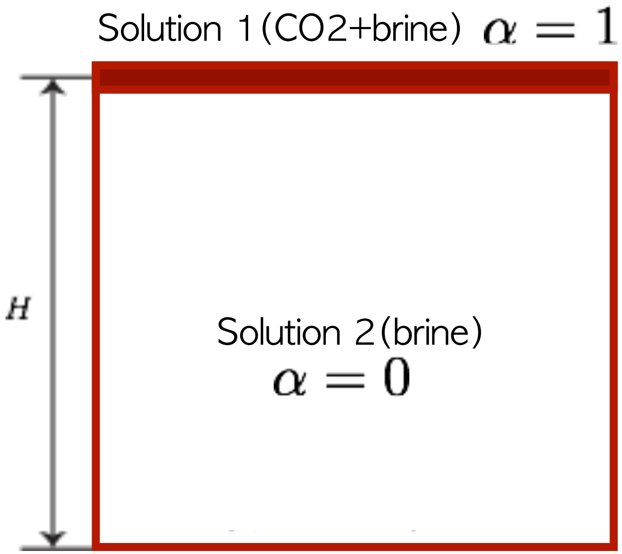
How do the flow patterns translate into the spatial organization of the permeability field through mineral dissolution?

How does this change affect flow and transport in turn?



Approach

High-resolution simulations in 2D and 3D



problem formulation

mixing ratio is defined as:

$$\alpha(x, z, t) = \frac{\mathrm{V}_{\text{solution 1}}}{\mathrm{V}_{\text{total}}}$$

$$\rho_{\text{mixture}} = \rho_2 + \Delta\rho\alpha$$

geochemical reactions

$$\mathrm{HCO_3^-} \rightleftharpoons \mathrm{CO_2 + H_2O - H^+}$$

$$\mathrm{CO_3^{2-}} \rightleftharpoons \mathrm{CO_2 + H_2O - 2H^+}$$

$$\mathrm{Ca^{2+}} \rightleftharpoons \mathrm{CaCO_3 - CO_2 - H_2O + 2H^+}$$

$$\mathrm{OH^-} \rightleftharpoons \mathrm{H_2O - H^+}$$

$$\phi \frac{\partial c_i}{\partial t} + \nabla \cdot (\mathbf{u} c_i) - \nabla \cdot (\phi D \nabla c_i) = -r_i$$

c_i: concentration of species i

update flow field

update porosity

The flow model

$$\nabla \cdot \mathbf{u} = 0$$

$$\mathbf{u} = -\frac{k(\phi)}{\mu}(\nabla P - \rho g \hat{z})$$

$$\rho = \rho_0 + \Delta\rho c$$

Summary – expected outcomes and impact

- The proposed work addresses some key aspects of CCS at scale
- In particular, public acceptance of CCS will require that concerns about leakage and seismicity triggered by CO_2 injection be addressed
- Predicting leakage and induced fault slip requires new tools
- This project contributes to the future deployment of this technology by analyzing the impact of CCS at the gigatonne-injection scale on storage security in the decade time period (CO_2 leakage and induced seismicity), and in the century time period (long-term CO_2 migration and trapping)

Organization chart

- Key personnel:

Ruben Juanes

Brad Hager

- All research performed at MIT

- Involves 2 PhD students and 1 postdoctoral associate

Birendra Jha

Xiaojing Fu

Benzhong Zhao

Gantt chart

Task	Subtask	Year 1		Year 2		Year 3	
1	1.0	1,2					
2	2.0	3					
	3.1		7	14			
3	3.2		8		17		
	3.3				18		
	3.4				19	24	28
	4.1	4,5	9,10	15	20		
4	4.2	6	11		21	25	
	4.3			16		26	29
	5.1		12				
5	5.2		13		22		
	5.3				23	27	30
	5.4						31,32

- No-cost extension requested:
  - Task 3: extend geomechanical model to quasi-dynamic formulation of fault friction
  - Task 5: complete simulations of CO2-brine system

Bibliography (1/3)

- B. Jha, F. Bottazzi, R. Wojcik, M. Coccia, N. Bechor, D. McLaughlin, T. A. Herring, B. H. Hager, S. Mantica, R. Juanes, Reservoir characterization in an underground gas storage field using joint inversion of flow and geodetic data. International Journal for Numerical and Analytical Methods in Geomechanics, 39, doi:10.1002/nag.2427 (2015).

- X. Fu, L. Cueto-Felgueroso, D. Bolster, R. Juanes, Rock dissolution patterns and geochemical shutdown of CO2-brine-carbonate reactions during convective mixing in porous media, Journal of Fluid Mechanics, 764, 296-315 (2015).

- R. Juanes, B. H. Hager, B. Jha, J. H. Shaw , A. Plesch, L. Astiz, J. H. Dieterich, C. Frohlich, D. Susanni, F. Colombo, L. Magagnini. Assessment of the potential for induced seismicity at the Cavone Oilfield: analysis of structural and geophysical data, and geomechanical modeling, OMC 2015 – O↵shore Mediterranean Conference, Ravenna, Italy, 24-27 March 2015.

- B. Jha and R. Juanes, Coupled modeling of multiphase flow and fault poromechanics during geologic CO2 storage, Energy Procedia, 63, 3313-3329 (2014).

- B. Zhao, C. W. MacMinn, and R. Juanes, Residual trapping, solubility trapping and capillary pinning complement each other to limit CO2 migration in deep saline aquifers, Energy Procedia, 63, 3833-3839 (2014).

Bibliography (2/3)

- B. Jha and R. Juanes, Coupled multiphase flow and poromechanics: a computational model of pore-pressure effects on fault slip and earthquake triggering. Water Resources Research, 50, doi:10.1002/2013WR015175 (2014).

- B. Zhao, C. W. MacMinn, H. E. Huppert, and R. Juanes, Capillary pinning and blunting of immiscible gravity currents in porous media. Water Resources Research, 50, doi: 10.1002/2014WR015335 (2014).

- M. L. Szulczewski, C. W. MacMinn and R. Juanes, Theoretical analysis of how pressure buildup and CO_2 migration both constrain storage capacity in deep saline aquifers. International Journal of Greenhouse Gas Control, 23, 113-118 (2014), doi:10.1016/j.ijggc.2014.02.006.

- M. L. Szulczewski, M. A. Hesse, and R. Juanes, Carbon dioxide dissolution in structural and stratigraphic traps. Journal of Fluid Mechanics, 736, 287-315 (2013), doi:10.1017/jfm.2013.511.

- J. J. Hidalgo, C. W. MacMinn and R. Juanes, Dynamics of convective dissolution from a migrating current of carbon dioxide. Advances in Water Resources, 62, 511-519 (2013), doi: 10.1016/j.advwatres.2013.06.013.

- J. Kim, H. A. Tchelepi and R. Juanes, Rigorous coupling of geomechanics and multiphase flow with strong capillarity. SPE Journal, 18(6), 1123-1139 (2013), doi:10.2118/141268-PA.

Bibliography (3/3)

- X. Fu, L. Cueto-Felgueroso, and R. Juanes, Pattern formation and coarsening dynamics in three-dimensional convective mixing in porous media. Philosophical Transactions of the Royal Society A, 371, 20120355 (2013), doi:10.1098/rsta.2012.0355.

- C. W. MacMinn and R. Juanes, Buoyant currents arrested by convective dissolution. Geophysical Research Letters, 40(10), 2017-2022 (2013), doi:10.1002/grl.50473.

- M. L. Szulczewski and R. Juanes, The evolution of miscible gravity currents in horizontal porous layers. Journal of Fluid Mechanics, 719, 82-96 (2013), doi:10.1017/jfm.2012.631.

- B. Zhao, C. W. MacMinn, M. L. Szulczewski, J. A. Neufeld, H. E. Huppert, and R. Juanes, Interface pinning of immiscible gravity-exchange flows in porous media. Physical Review E, 87, 023015 (2013), doi:10.1103/PhysRevE.87.023015.

- J. J. Hidalgo, J. Fe, L. Cueto-Felgueroso and R. Juanes, Scaling of convective mixing in porous media. Physical Review Letters, 109, 264503 (2012), doi:10.1103/PhysRevLett.109.264503.

- R. Juanes, B. H. Hager, and H. J. Herzog, No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful. Proc. Natl. Acad. Sci. U.S.A., 109(52), E3623 (2012), doi:10.1073/pnas.1215026109.